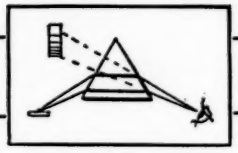
Journal of the

OPTICAL SOCIETY *of* AMERICA

VOLUME 28
No. 2



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Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
175 Fifth Avenue, New York, N. Y.
FOR AND UNDER THE EDITORIAL SUPERVISION OF
THE OPTICAL SOCIETY OF AMERICA

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Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 28 FEBRUARY, 1938 NUMBER 2

The "Drift Effect" in Selenium Photovoltaic Cells

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(Received November 30, 1937)

The photo-current in a selenium photovoltaic cell varies with time even if constant conditions be maintained. This variation consists either in a decrease or an increase of current, the current approaching a constant value in the course of about ten minutes. Whether the initial change of current is a decrease or an increase seems to be independent of the particular type of cell but is determined by the wave-length of the incident radiation and possibly also in certain cases by the temperature of the cell. If the cell is exposed to light from incandescent lamps, the effect is dependent on the temperature and will vanish at a certain temperature. The phenomenon is not an effect of fatigue; a more suitable name for it would be "initial effect."

DURING the few years which have elapsed since the selenium photovoltaic cell was put on the market it has been used extensively for various measurements of light. For accurate quantitative investigations, however, its usefulness has proved somewhat limited by certain less favorable attributes, among which the so-called "drift effect" is certainly the chief source of disturbance. This effect manifests itself as a change in the photo-current during the initial stage of exposure to light, in spite of constant conditions being maintained.

A number of shorter accounts of this drift effect, referring both to selenium and to cuprous oxide cells, have been published already, but there seems hardly to exist any agreement as to the conclusions reached. The principal points observed are:

1. When the cell is first illuminated, a certain photo-current is obtained, which seems generally to decrease during continued constant illumination. The decrease first proceeds rapidly, but gradually slows down, the current approaching a certain final value.[1-3]

2. The time required for the current to reach its final value depends on the duration of the preceding dark period.[2, 4] Regarding the length of this time, statements differ considerably: from 15 minutes[5] to 150 hours[6] (Cu_2O cell).

3. There are only a few authors who mention an increase of the initial value of the photo-current ("Kriecheffekt").[7-9]

4. The drift effect is different for different wave-lengths. It is stated to be greatest for infra-

[1] A. Goldmann, M. Lukasiewitsch, Physik. Zeits. **34**, 66–73 (1933).
[2] W. Grundmann, Loni Kassner, Physik. Zeits. **35**, 16–20 (1934).
[3] G. Marchal, L. Marton, Rev. d'optique **15**, 3–9 (1936).
[4] O. H. Knoll, Das Licht **5**, 167–172 (1935).
[5] Mitteilung a. d. Lab. N. V. tot Keuring v. Arnheim, Licht u. Lampe **21**, 131–134 (1932).
[6] W. Bulian, Physik. Zeits. **36**, 33–34 (1935).
[7] H. C. Hamaker, W. F. Beezhold, Physica, **1**, 119–122 (1933).
[8] B. Lange, *Die Photoelemente und ihre Anwendung* (Leipzig, 1936), I, s. 119.
[9] R. Sewig, A.T.M. **5**, 422–3 (1937).

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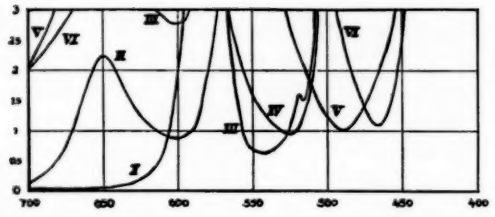

FIG. 1. Extinction curves for the filter combinations used.

red.[1, 7, 4] As a consequence, it would be possible to eliminate, or at least to diminish, the effect by absorbing the infrared radiation in a water filter. Another author, however, contests this statement.[10]

Our principal aim in investigating the drift effect was to ascertain its dependence on wave-length and temperature. The cell examined was of the E. Zierold make, type 25E, fitted with a color correction filter designed according to Dresler. It was placed in an electric oven and connected by a 20-ohm shunt to a Kipp and Zonen galvanometer having an extremely short period of oscillation (Moll microgalvanometer). The galvanometer was mounted so as to register on a drum covered with photographic paper. Between the source of light and the photo-cell, a liquid filter (solution of Mohr's salt) was inserted to absorb the infrared radiation.

Comparative tests made with other cells, for instance SAF, without color correction filter, showed that these cells behave like the Zierold cell.

Exposures were made at three temperatures, 25, 40 and 50°C. The color of the incident radiation was varied by means of the following filter combinations (Fig. 1):

	Filter	Absorption minimum
I	Wratten 29	650 mμ
II	" 25+90	600 "
III	" 61+77	540 "
IV	" 15+65A	525 "
V	" 8+47	490 "
VI	" 3+50	470 "

The luminous intensity of the lamp was modified for each color so as to produce a constant photo-current (1.6×10^{-7} amp.). The drift effect was followed by the registering drum for ten minutes, which proved a sufficient time for forming a complete picture of the phenomenon. Between each exposure a pause of at least 30 minutes was interposed.

Figure 2 is a copy of a series of galvanograms.

The following results were obtained from the investigation:

1. After 10 minutes, approximately, the photo-current is practically constant, irrespective of the character of the curve and the wave-length of the light.

2. In one and the same cell the drift may be either an increase or a decrease of the photo-current.

3. Under blue or bluish green illumination, the photo-current will sink at the start to a greater extent and more rapidly according as the wave-length is shorter. At some point between 490 and 525 mμ the drift disappears, and the photo-current becomes constant. In green light the drift is positive, the photo-current increasing after the initial throw and arriving at a final value comparatively quickly. For a certain wave-length in yellowish green the drift again vanishes, and the photo-current is constant from the

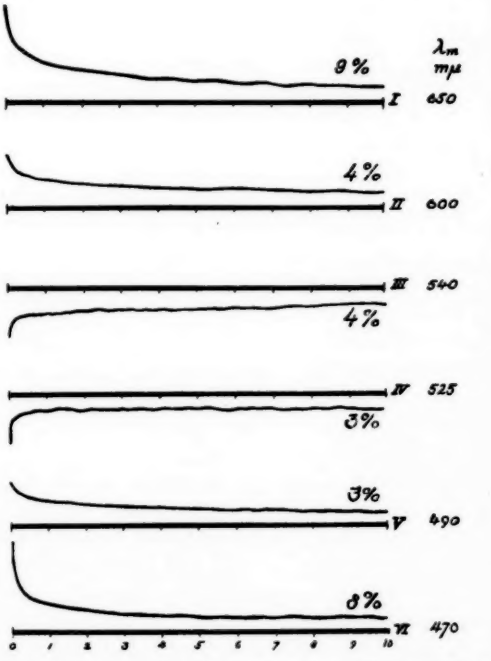

FIG. 2. Development of drift effect during illumination of photo-cell with different regions of the spectrum. Percentage figures indicate size of deviation from final value of photo-current.

[10] J. S. Preston, J. Inst. Elect. Eng. 79, 424–434 (1936).

moment the illumination sets in. In orange and red the decrease of the photo-current reappears, and the change is greater and more marked according as the wave-length is greater.

4. For the temperature interval of 25–50°C examined, the progress of the drift seemed practically unvarying for the different isolated regions of the spectrum.

5. The drift showed an obvious temperature dependence, however, when the incident radiation was composed of a mixture of different regions of the spectrum. If the source of light was a cinema lamp, 500 watts, 110 volts, burning on 24 volts, the effect proved negative at a lower temperature, i.e. the photo-current dropped from its initial value. At a higher temperature the character of the drift shifted over to the positive side resulting in an increase of the initial value of the photo-current. The turning point was found to lie near 37°C where the drift practically vanished.

A similar development was observed when a blue (resembling daylight blue) glass had been inserted (40 volts applied), although in this case the drift showed a tendency of turning already below the temperature range studied (35–45°C).

6. Under illumination of the cell with light from a mercury lamp (v. Hippel), no temperature dependence was observed. In this case all curves were decidedly rising, apparently in consequence of the dominating Hg line, 546 mμ, which itself produces a rising characteristic.

The trials made with mixed light are only preliminary but indicate clearly enough that a certain temperature of the photo-cell may be fixed at which the drift effect does not occur under exposure of the cell to light from lamps such as for instance ordinary lamps of the standard series. Consequently it is possible to take exact photometric measurements of such lamps by means of selenium photovoltaic cells while maintained at that special temperature.

A theoretical explanation of the drift effect has been attempted, in the first place by Lange, but his theory does not suffice to explain the new phenomena here reported. Evidently these phenomena cannot be interpreted as an effect of fatigue, as is often done especially by German and French authors. A more appropriate, unbiased and international denomination of the phenomenon would be, for instance, "initial effect."

Book Review

Proceedings of the International Commission on Illumination. Ninth Session, Berlin and Karlsruhe, Germany, July, 1935. *Reports on Undertakings and Minutes of Sessions.* Pp. 680, illustrated, 15×23 cm, cloth covers. Cambridge University Press, London, 1937. Price 1£.

The text consists of 25 reports of technical committees, several related papers, the discussion of the reports at sessions and resulting recommendations of the commission. In addition there are reports of three plenary sessions of the commission, lists of delegates and other general information.

Each technical committee report treats of a topic assigned at the 1931 session and gives the information, data and other information secured by the National Committee to which the respective Secretariat had been delegated, in correspondence with all other National Committees. In a few cases interim meetings were held. The reports are in English, French or German, ten being in English, six predominantly in German and the remainder in French. The reports in English include Lighting Practice, Lighting Education, Mine Lighting, Artificial Daylight, Colors for Signal Glasses, Traffic Signals, Aircraft Lighting, Ground Lighting for Aviation, Factory and School Lighting and Glare.

Resistance in Selenium Photovoltaic Cells

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(Received November 30, 1937)

1. INTRODUCTION

SEVERAL authors[1–4] already have investigated the resistance in photo-cells of the so-called blocking layer type, and have discovered that it depends on the illumination of the cell and the current passing through it, no matter whether this current is generated by the cell itself or is delivered from an outside source. The resistance of the cell in one direction has been observed to decrease under increasing amperage, while in the other direction it is stated to be constant.[5] Thus a rectifying effect should result, especially when larger currents are used. No complete diagram, however, seems to have been published on the changes observed. In view of certain tests indicating that the above relations do not apply in the case of very small currents, we have reinvestigated the question.

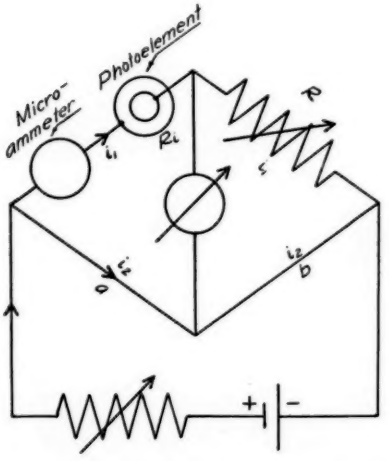

FIG. 1. Wiring diagram used in determining the resistance of the photo-cell.

[1] L. O. Grondahl, Rev. Mod. Phys. **5**, 141–165 (1933).
[2] P. Lange, *Die Photoelemente und ihre Anwendung. I.* (Leipzig, 1936).
[3] J. T. MacGregor, R. M. Billington, J. I. E. F. **79**, 435–444 (1936).
[4] R. Sewig, *Objektive Photometrie*, (Berlin, 1935).
[5] L. A. Wood, Rev. Sci. Inst. **6**, 196–201 (1935).

2. METHOD

The object of the examination was to determine the resistance of the photo-cell as a function of the current passing through it. For this purpose a selenium photovoltaic cell (supplied by Zierold, Berlin), provided with a Dresler compensation filter[6] was chosen. The resistance was measured by a Wheatstone bridge (Fig. 1), and the current by a microammeter (or, for the smallest currents, by a galvanometer) connected in the branch of the bridge in which the photo-cell was placed. Since the resistance of these instruments was only 240 and 100 ohms, respectively, it could be neglected in comparison with the resistance of the photo-cell, which was in excess of 10,000 ohms.

The latter resistance we will designate by R_i; the current through the cell or its branch of the bridge by i_1. E denotes the electromotive force produced in the cell under illumination; a and b the resistance in the other branches of the bridge; i_2 the current through the branches a and b. See Fig. 1.

The battery current could be changed by a regulating resistance, and could be made to flow either way through the cell.

Absence of current in the galvanometer G gives the following relations, according to Kirchhoff's law:

$$\begin{aligned} &R_i i_1 - a\cdot i_2 = E;\\ &R\cdot i_1 - b\cdot i_2 = 0;\\ &\therefore R_i = (a/b)R + E/i_1. \end{aligned} \qquad (1)$$

In Eq. (1) R_i is the sum of two terms the first of which is obtained directly from the data of the bridge, while in the second only i_1 can be read directly. E was determined independently by measuring the electromotive force of the cell for a number of different illuminations B with the aid of a compensating apparatus. Further the current i_f produced by the same illumination was measured, the photo-cell retaining its con-

[6] A. Dresler, Das Licht **3**, 41–43 (1933).

nection in the bridge though of course with the battery circuit opened. Now, according to Elvegård,[7] both $E^{-\frac{1}{2}}$ and $i_f^{-\frac{1}{2}}$ depend linearly on

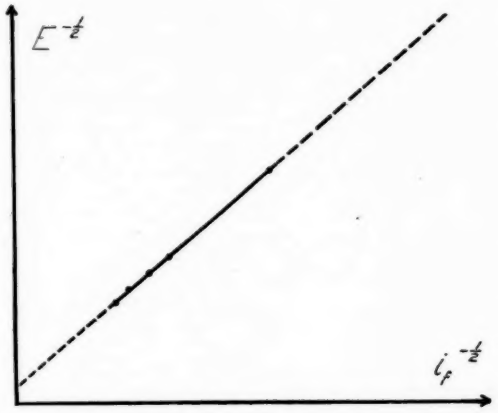

FIG. 2. Computation of e.m.f. in the photo-cell.

$B^{-\frac{1}{2}}$. In consequence a straight line is obtained when $E^{-\frac{1}{2}}$ is plotted against $i_f^{-\frac{1}{2}}$ as in Fig. 2. Thanks to this rectilinearity, the curve could be extended with great exactitude beyond the range of E accessible to direct measurement with the compensation apparatus. By reading the photoelectric current i_f for each illumination used during the measurement of resistance it was easily possible afterwards to compute the corresponding value of E from the diagram. Every quantity in Eq. (1) was then known for the calculation of R_i.

The following sources of error had to be considered in determining the resistance: (a) the dependence of the resistance on the time, the current being constant; (b) the dependence of the resistance on the temperature, the current being constant; (c) the dependence of the electromotive force on the temperature, the current being constant.

(a) It appeared that a certain time was required, after the current had started, for the resistance to become constant. The variations of the resistance during this interval amounted to about 3 percent, maximum. However, the time needed to make a measurement by the Wheatstone bridge was sufficient to allow the resistance to become constant.

[7] E. Elvegård, Physik. Zeits. **37**, 129–133 (1936).

(b) The dependence of the resistance on the temperature is treated more exhaustively in paragraph 4. From Tables I and II it is evident that the maximum variation is about 3 percent per degree. In the present measurements the temperature variations did not exceed 2°C. Although the resulting error in the resistance is appreciable, it is of no consequence as regards the shape of the curves reproduced in this article.

(c) In determining the alteration of the electromotive force E due to changing temperature, a value of about 1 percent per degree centigrade was obtained for a photoelectric current of about 10 μA. The resulting error in the determination of resistance consequently is of the same order as the errors mentioned under (a) and (b).

In order to reduce the above errors, attributable to temperature fluctuations, means were adopted to maintain the temperature of the photo-cell as constant as possible during the illumination. Among other things, the cell was exposed to the action of green light (the infrared rays having been filtered out) coinciding with the maximum sensitivity of the cell, thus admitting a minimum supply of energy for obtaining a certain photoelectric current and suppressing as far as possible the heating of the cell.

3. Dependence of Resistance on Current Intensity

The results of the measurements are shown in Fig. 3.

The curve marked "dark" refers to the photo-cell in the dark, and the others refer to the cell exposed to light of different intensities. The ordinates are the resistance R_i of the photo-cell, calculated from the formula (1). For abscissa has been chosen the total current i through the cell as given directly by the microammeter in Fig. 1; i.e., the photoelectric current proper, i_f, plus the battery current i_b through the photo-cell branch of the bridge; or minus i_b if it flows opposite to the photoelectric current.

Thus $$i=i_f+i_b.$$

The points P indicate the spots where $i_b=0$, i.e., where only the photoelectric current passes through the cell. Between the axis of ordinates

TABLE I. *Direction opposite to photo-current, if cell illuminated.*

CURRENT IN AMPERES	TEMPERATURE COEFF. OF RESISTANCE/° C	RESISTANCE IN OHMS AT 25° C	ALTERATION PER DEGREE %
1.69×10^{-7}	3.5×10^{3}	200×10^{3}	1.8
5.73	2	135	1.5
31.5	0.5	53	0.9
55.0	0.25	37	0.7

TABLE II. *Direction same as that of photo-current, if cell illuminated.*

CURRENT IN AMPERES	TEMPERATURE COEFF. OF RESISTANCE/° C	RESISTANCE IN OHMS AT 25° C	ALTERATION PER DEGREE %
1.74×10^{-7}	9.5×10^{3}	360×10^{3}	2.6
5.03	14	455	3.1
30.7	5	370	1.4
58.2	1	305	0.3

and the points P, i_b is negative or runs in the direction opposite to i_f, but is of smaller absolute value than i_f. Thus the photoelectric current exceeds the battery current, and in this region no resistance measurements are possible with the bridge. For this reason the curves are dotted here.

At $i=0$ the photoelectric and the battery currents compensate each other, and the cell becomes currentless. For negative values of i the (negative) battery current exceeds the photoelectric current; i is opposite to i_f.

As shown by the curves, the resistance undergoes remarkable changes. When the photo-cell is traversed by infinitely small currents, the resistance is equal in both directions, in agreement with Wood's statement. However, a small change of current will affect the resistance very promptly. In one direction the resistance will increase; in the other direction it will decrease. For this reason a marked rectifying effect is developed. In the former case, the resistance rises to a maximum at a certain, comparatively low current; then with further increase in current, it decreases. It is chiefly the latter part of the curve that has been previously dealt with in the literature. The maximum is particularly conspicuous with the cell unilluminated. As to the current of the other direction, the resistance uniformly decreases in proportion as the current

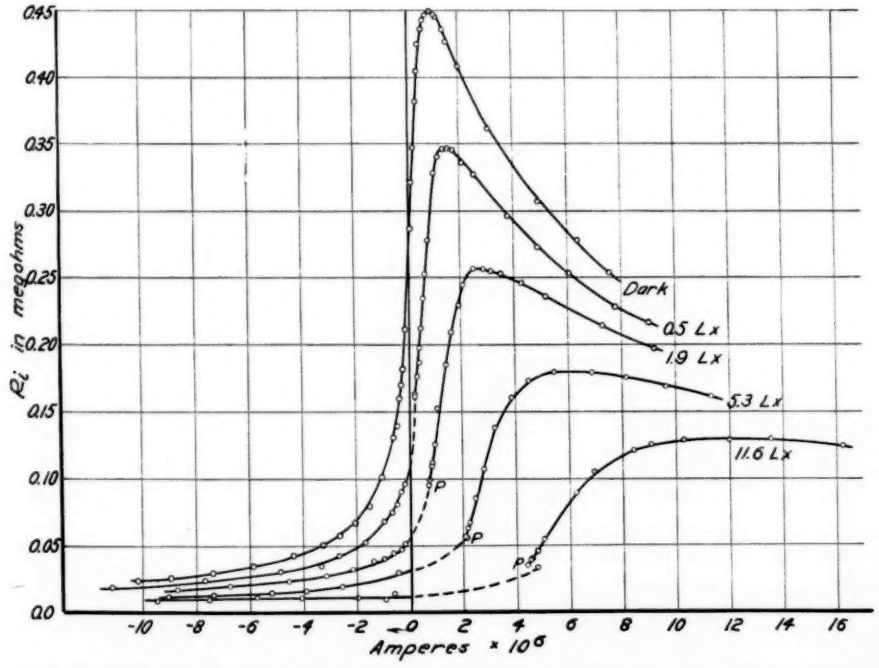

FIG. 3. Change of resistance due to the passage of currents of different intensities through photo-cell, and to different illuminations.

increases, and seems to approach a constant limiting value.

Under illumination of the photo-cell a general reduction of the resistance ensues. This reduction comes out prominently at the maximum, which is depressed considerably and becomes flatter as the illumination is increased. At the same time it moves towards larger current intensities. When i is opposite to i_f the influence of the illumination is less marked. However, even here the resistance shows some reduction, especially when very small currents are concerned. The greater the illumination, the less does the resistance depend on the current, as shown by the flattening of the curves. It seems as if for this direction both the illumination and the current supplied from without would make the resistance approach a certain constant value.

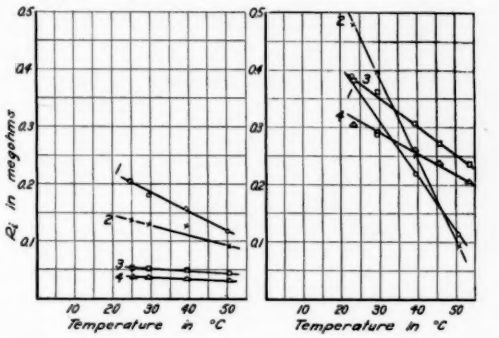

FIG. 4. Change of resistance in photo-cell with change of temperature for currents of different intensities. *a* (left), Current supplied flows in direction opposite to that of photo-current. *b* (right), Current supplied flows in same direction as that of photo-current.

4. Dependence of Resistance on Temperature

The dependence of the resistance on the temperature is shown in Fig. 4. For this measurement, instead of a Wheatstone bridge, a potentiometer, combined with volt- and ammeters, was used for determining the fall of potential and the current, respectively, of the photo-cell; from which data the resistance was computed. Each curve represents the relation for a specified current delivered from an outside source through the dark cell. In Fig. 4*a* this current is opposite to the current that would have resulted if the cell had been illuminated; in Fig. 4*b* it is in the same direction. Owing to the change of R_i with i, a pair of curves is obtained for each current. The currents are so selected that for curves 1 the current lies between the axis of ordinates and the maximum in the dark curve of Fig. 3; for curves 2, it coincides approximately with the maximum; and for curves 3 and 4 it corresponds to the downward branch to the right in Fig. 3.

Figure 4 shows a linear decrease of the resistance with increasing temperature. The different inclination of the curves proves that not only the resistance, but also its temperature coefficient depends upon the current through the cell. The temperature coefficient is negative throughout. In the direction of the photoelectric current its absolute value is first increased under increasing current and reaches a maximum (curves 1 and 2, Fig. 4*b*), which probably sets in just at the current at which the resistance itself is a maximum. Apparently the photo-cell is very unsteady in this region. If the increase in current is continued, the absolute value of the temperature coefficient will drop again (curves 3 and 4, Fig. 4*b*).

When it is opposite to i_f, the change of the temperature coefficient takes a different course. Here its absolute value drops regularly with increasing current (curves 1–4, Fig. 4*a*); i.e., the dependence of the resistance on the temperature is lessened. The stability which the resistance approaches under the influence of large currents, apparently also applies to its sensitivity to temperature fluctuations.

Tables I and II give the temperature coefficient and the percentage of variation per degree, of the resistance at 25°C.

Intensity of the Continuous Spectrum of Hydrogen *

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(Received November 24, 1937)

In order to construct a most intense source of the continuous spectrum of hydrogen, the most favorable conditions were systematically investigated. The intensity varied linearly with the current density except for very high current densities where it varied less rapidly. The pressure for a maximum of intensity was found to be a function of the current density and practically varied from 1 to 2 mm. A study of the relation of the intensity to length, surface, and cross section of the capillary was made. On the basis of these results a powerful source of the continuum was constructed. This source was compared with the positive crater of the carbon arc and found to be superior in intensity below 2925A.

PREVIOUS WORK

RECENT work on the absorption spectra of unstable molecules carried on at this laboratory required an intense source of continuous ultraviolet radiation as an absorption background. The most uniform source with regard to wave-length and time is the continuous spectrum of molecular hydrogen. Various shapes of hydrogen discharge tubes have been described.[1] The remaining problem is a *systematic* investigation of the conditions leading to the highest intensity. The solution of this problem is the purpose of the present paper. For a general survey of the properties and origin of the hydrogen continuum the papers of Chalonge,[2] Finkelnburg,[3] and Richardson[4] are excellent.

It is to be expected that optimum values of pressure and current density exist for the production of the maximum intensity of the continuous spectrum. For very high *pressure* the power required becomes excessive.[5] For very high *current density* the hydrogen is dissociated; and the molecular spectrum, of which the continuum is a part, disappears as observed in Wood's[6] hydrogen discharges. Although this effect can be partly compensated for by proper treatment of the glass wall, for a given tube an optimum current is to be expected.

INTENSITY WAVE-LENGTH CURVE

In order to choose a method of measuring intensity, it was necessary to determine if the intensity wave-length curve varied with the current and pressure.

The theory of Winans and Stueckelberg[7] in which the continuous spectrum is emitted in transitions from various vibrational levels of an upper stable electronic state to a lower unstable electronic state suggests that changes in the conditions of excitation may produce changes in the intensity distribution with wave-length. Marked changes in the intensity distribution have been observed in hydrogen-helium and hydrogen-neon mixtures. The results were reported previously.[8] As the addition of a rare gas does not increase the intensity, we are concerned only with discharges in pure hydrogen.

Plates were exposed with a small quartz spectrograph to discharges in pure hydrogen at pressures from 0.055 to 4 mm and with current

* An extract from a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Harvard University.

[1] Z. Bay and W. Steiner, Zeits. f. Physik. **45**, 337 (1927); E. O. Lawrence and N. E. Edlefsen, Rev. Sci. Inst. **1**, 45 (1930); G. B. Kistiakowsky, Rev. Sci. Inst. **2**, 549 (1931); H. C. Urey, G. M. Murphy and J. A. Duncan, Rev. Sci. Inst. **3**, 497 (1932); W. M. Powell, Jr., Phys. Rev. **45**, 154 (1934); O. Darbyshire, J. Sci. Inst. **10**, 322 (1933); H. J. J. Braddick, Proc. Camb. Phil. Soc. **30**, 355 (1934); Daniel S. Stevens, Rev. Sci. Inst. **6**, 40 (1935); **6**, 260 (1935); W. H. Watson and D. G. Hurst, Can. J. Research **13**, 19–21 (1935); R. H. Munch, J. Am. Chem. Soc. **57**, 1863 (1935); H. C. Gull and A. E. Martin, J. Sci. Inst. **12**, 379 (1935); F. Almasey and G. Kortüm, Zeits. f. Elektrochem. **42**, 607 (1936); G. Jacobi, Zeits. f. tech. Physik **17**, 11, 382 (1936); Physik. Zeits. **37**, 808 (1936); G. Déjardin, Rev. Trimestr. Canadienne **23**, 238 (1936).

[2] D. Chalonge, Ann. de physique **1**, 123 (1934).

[3] W. Finkelnburg, Physik. Zeits. **31**, 1 (1930) and **34**, 529 (1933).

[4] O. W. Richardson, *Molecular Hydrogen and Its Spectrum* (Yale University Press, 1934).

[5] Moreover, a large part of the power is wasted as heat because of impacts of the second kind.

[6] R. W. Wood, Proc. Roy. Soc. **A102**, 1 (1922).

[7] I. G. Winans and E. C. G. Stueckelberg, Proc. Nat. Acad. Sci. **4**, 867 (1928).

[8] N. D. Smith, Phys. Rev. **49**, 345 (1936).

densities from 2 to 66 ma/mm². No changes in the intensity distribution were observed from a visual examination of the plates although changes of the order of 10 percent could have been detected. Gonsalves,[9] Chalonge,[2] and D. Barbier, D. Chalonge, H. Kienle and J. Wempe[10] made studies of the hydrogen discharge with a view to using it as a standard for intensity measurements in the violet and ultraviolet. They found that considerable changes in current and pressure produced changes of only a few percent in the intensity distribution.

Consequently for our purpose it is sufficient to measure the intensity of the continuous spectrum at a single wave-length in order to determine the effects of changes in pressure and current.

Intensity of a Selected Wave-Length Range of the Continuous Spectrum as a Function of the Pressure and Current Density

Photographic method

In order to obtain high current densities without overheating the capillary, the current was interrupted by a mechanical interrupter driven by a synchronous motor. Such a procedure is actually used in the investigation of rapid gas reactions by absorption spectra. Difficulty was had in measuring this pulsating current, but finally a modification of a method by Reiss[11] for measuring radiofrequency currents was used.

An enlarged image of the capillary was focused on the slit of a small quartz spectrograph. An exposure was made with the lowest current used. A series of exposures of the same time and with different currents and constant pressure was then made with a calibrated wire gauze screen placed over the condensing lens These currents were chosen about that one which, on the assumption of a linear variation of intensity with current, should give the same intensity with the screen as the first current without the screen. By interpolating between the densities of the various exposures, the current was determined at which the ratio of intensity was equal to the reciprocal of the transmission factor of the screen.

The results of these measurements are shown in Fig. 1. These points were plotted from two of the best plates taken with the pressure constant at 0.5 mm. Since the exact shape of the current pulse was not known, the values of current density were estimated by assuming a square-topped pulse. On this basis the maximum current of 57 ma represents a current density of 323 ma/mm². The deviation from linearity at the highest current density cannot be given great weight from this experiment alone even though errors due to arcing at the interrupter at the high current densities should increase the intensity.

The results of the photographic method served to check the results of the photoelectric method described below.

Photoelectric cell method

Since no large changes in the energy distribution with wave-length were found for various current densities, it was possible to dispense with the spectrograph and use a photoelectric cell screened by a filter which transmitted a band of the continuous spectrum. A caesium hydride vacuum cell with a thin glass envelope was used with a Corex red purple filter. The cell had a maximum sensitivity at 3500A and was sensitive down to 2900A. It had a secondary maximum at 6500A. The filter was 4 mm thick and transmitted wave-lengths between 4000A and 2800A and a small percent above 7000A. The addition

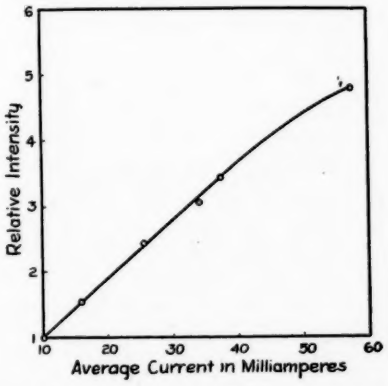

FIG. 1. Curve showing the intensity of the continuous spectrum for 0.5 mm of hydrogen as a function of the current.

[9] V. E. Gonsalves, Physica **2**, 1003 (1935).
[10] D. Barbier, D. Chalonge, H. Kienle and J. Wempe, Zeits. f. Astrophys. **12**, 178 (1936).
[11] Reiss, *Handbuch der Physik*, Vol. 16 (Geiger and Scheel) (Julius Springer, 1927), p. 339.

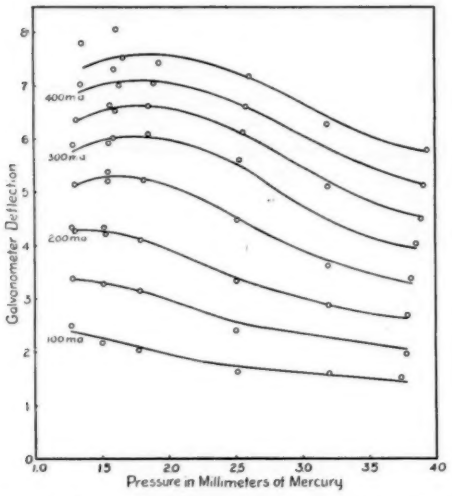

FIG. 2. Curves showing the intensity of the continuous spectrum as a function of pressure for constant current.

to the system of a deep red filter, which absorbed the ultraviolet, reduced the photoelectric current to less than 2 percent of its former value when exposed to a hydrogen discharge. Hence the cell and filter had a maximum response at 3500A and the sensitivity decreased rapidly to the longer wave-lengths. The intensity of the source was such that a galvanometer could be used to measure the photoelectric current. The hydrogen discharge was operated without the interrupter.

The photo-cell was calibrated with the continuous spectrum in the range of current densities where the intensity was known to be a linear function of the current density. The response was found to be linear within a percent of the full scale deflection. The photo-cell was mounted so that it could be moved away from the source in order to use the same portion of the response curve of the cell for all measurements. Hence the galvanometer deflections were always proportional to the intensity.

The discharge tube used in this experiment was similar to the final tube shown in Fig. 5. As the length of the capillary was to be investigated later in detail, a short capillary 5 mm long with a rectangular cross section 0.7 by 3.4 mm was used. The interior of the capillary was platinized by painting it inside with a solution of platinum chloride in nitrobenzene. After being thoroughly dried by a current of air, it was baked several hours in an electric furnace at 500°C. The baking broke down the salt leaving a residue of finely divided platinum.

The tube was evacuated and washed several times with pure hydrogen during a heavy discharge. This process was continued until plates taken with a small quartz spectrograph showed no impurities. The photoelectric cell and filter were then placed in front of the tube and the intensity measured for various currents and pressures. At the beginning of a run, the reading of the galvanometer did not become steady for thirty or forty minutes. It was necessary to wait ten to twenty minutes between readings when the current was changed. The intensity is plotted in Fig. 2 as a function of the pressure for a series of currents—it being relatively easy to adjust the current to a desired value. From this set of curves the curves in Fig. 3 were plotted showing the intensity as a function of the current at constant pressure. The currents used—100 to 450 ma—correspond to current densities of 42 to 189 ma/mm^2.

An accident destroyed the capillary, and it was replaced with a quartz capillary sealed into the tube with quartz-to-Pyrex graded seals. With the tube in this form the intensity was measured for currents up to 1700 ma. The results were not so consistent as with the former tube. There were random variations of a few percent and a gradual and continuous falling off in intensity

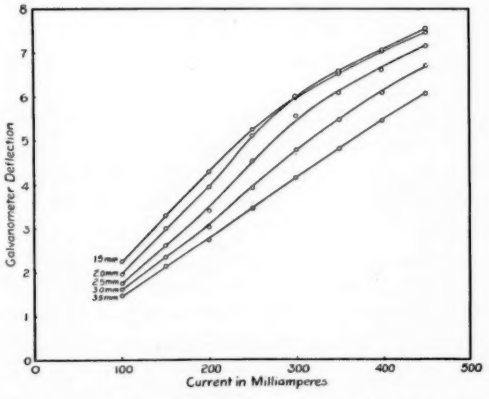

FIG. 3. Curves showing the intensity of the continuous spectrum as a function of current for constant pressure.

which finally amounted to 15 percent after two weeks. When the tube was taken down it was found that the constriction in the capillary had been eaten away so that at one end it had twice its former area. This erosion, although known in intense spark discharges, was a complete surprise, for the maximum current density used was only 410 ma/mm². Consequently most of the data obtained with this tube had to be discarded. However, the change was gradual and from some of the first runs which were consistent the curve in Fig. 4 was plotted. The current of 1700 ma corresponds to 410 ma/mm².

The curves in Fig. 2 show that the pressure for maximum intensity is a function of the current density. The curves in Figs. 3 and 4 show that the intensity increases less rapidly with increasing current at high current densities than at low current densities.

This kind of relation is to be expected for two reasons. First, high current densities should partially dissociate the hydrogen molecules and so quench the molecular spectrum—in spite of the platinized capillary walls which favor recombination. It is known that in strong spark discharges in hydrogen only the atomic spectrum is emitted.

Secondly, an intense local heating of the gas takes place in the capillary. The total pressure remains constant because of the large total volume of the system, and hence the local density of the gas within the capillary decreases. The effect is equivalent to a decrease in pressure.

These results agree with those of Bay and Steiner, who used a maximum current density of 25 ma/mm², and with those of Lawrence and Edlefsen who used a maximum current density of 169 ma/mm². The practical result is that the deviation from linearity is rather small; and hence—apart from spark discharges—it is worth while making the current density as large as possible.

During the work with the photoelectric cell, the discharge tube was operated on direct current, and a much greater intensity was observed when the front electrode was the cathode. Plates were then made with a small quartz spectrograph illuminated with the discharge in a rectangular hollow cathode which showed that the continuous spectrum was emitted strongly

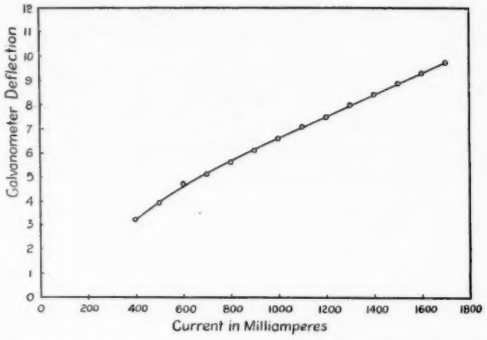

FIG. 4. Curve showing the intensity of the continuous spectrum as a function of current.

in the negative glow. This result is not of great interest in the design of sources for absorption spectroscopy; for the current density viewed by the spectrograph cannot be made large without an excessive length of cathode.

The capillary

In a long narrow capillary the rear portion cannot contribute a considerable share of the intensity since the aperture through which it is viewed is limited by the front opening of the capillary. This intensity is augmented, however, by reflection from the walls.

Two discharge tubes were constructed and mounted with the two capillaries parallel and close together so that they could be covered by a single plane of quartz and viewed simultaneously by a quartz spectrograph. The relative intensities were then determined from a series of exposures made with calibrated wire gauze screens. The capillaries were 38.6 cm and 11 cm long, respectively, and were made from the same piece of 5 mm inside diameter Pyrex tubing. The ratio of the intensities was 2.5 while the ratio of the lengths was 3.5.

These measurements showed that it was profitable to increase the length of the capillary to gain intensity. On the other hand the actual field of light from such a source will not illuminate a condensing lens or collimating lens of a spectrograph evenly, and hence the resolving power of the instrument will be affected. Such problems must be considered in using a particular discharge tube and spectrograph as no general solution can be given.

It has generally been recognized on the basis of the work of Wood and Langmuir that metal surfaces favor recombination and so enhance the intensity of the continuous spectrum. Bonhoeffer[12] observed the heating of different metals placed in a Wood's hydrogen discharge tube. The heating is explained by assuming the recombination of the atoms to take place on the metal. Bonhoeffer found that platinum gave the largest heating, and from our point of view then platinum was the most desirable surface for the capillary. Moreover it is easy to apply and is durable, probably more so than silver.

A capillary with a large cross-sectional area wastes energy. Hence in the tube of Jacobi[13] optimum conditions were not realized in spite of the large total current (10 amperes) because of the large diameter of the capillary. Also in a large diameter capillary the ratio of surface to volume, important for recombination, is small. The opposite extreme is realized by F. Almasey and G. Kortüm[14] who placed a porcelain constriction in the capillary. However, the porcelain is not cooled efficiently, and consequently this method does not favor the *molecular* spectrum since recombination is slower with increasing temperature. We feel that the capillary should have the shape which gives the largest ratio of surface to volume directly cooled. Hence a rectangular cross section with a narrow base and thin wall is desirable.

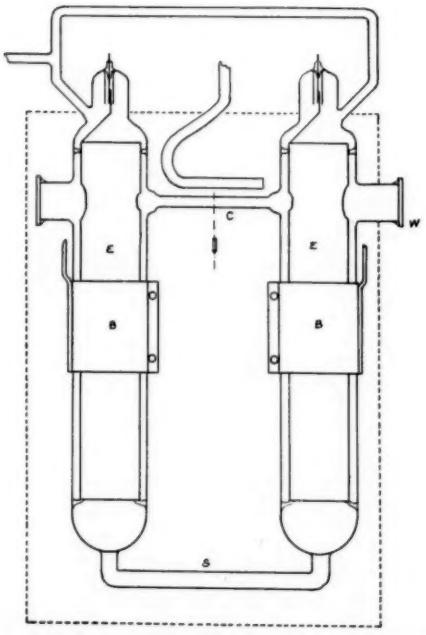

FIG. 5. Diagram of the final discharge tube.

Another advantage of a narrow rectangular cross section is in using a discharge tube with a spectrograph. The part of the image of the capillary not on the slit is simply wasted. It is the intensity per unit area which is important. The flat capillary furnishes an image of large intensity per unit area in a region that is useful for the spectrograph.

The quartz window

Clear fused quartz is generally used as a window for hydrogen discharge tubes. Difficulty is experienced with a photochemical change that colors the quartz a blue-violet and seriously decreases its transmission in the near ultraviolet. Darbyshire[15] experienced this same difficulty, but he was able to avoid it by the use of crystalline quartz. However, it appears that he was most fortunate in his selection of the quartz crystals, for Dr. Schneider, formerly of this laboratory, assured us that crystalline quartz generally discolors in the same way as fused quartz. The discoloration may be removed easily by heating the window on a steel plate with a bunsen burner to about 300° or 400°C. If the window is subject to electron bombardment, a surface discoloration occurs which can only be removed by polishing.

For a discharge tube which is to be used over a long period of time or which is to be used as a standard it might be desirable to use a window of fused quartz connected to the rest of the tube by means of a graded seal. A small electric furnace placed over the window and kept at about 250°C while the tube is in use should keep the window permanently clear. A permanent magnet could be placed near the window to deflect electrons if the design of the tube so required.

[12] K. F. Bonhoeffer, Naturwiss, **6**, 201 (1927).
[13] G. Jacobi, reference 1.
[14] F. Almasey and G. Kortüm, reference 1.
[15] O. Darbyshire, reference 1.

Design of the final discharge tube

Figure 5 is a diagram of the final discharge tube. The electrodes, *E*, were made from aluminum tubing 28 cm long and 4.3 cm in diameter. A flat platinized capillary,[16] *C*, 5.3 cm in length with a cross-sectional area of 7.8 mm² (1.3 mm×6 mm) was used. The two large tubes containing the electrodes were held together by a heavy Pyrex rod, *S*, fused to the ends of the tubes. They were braced at the top by a Pyrex tube sufficiently long so that the discharge would not pass through it in preference to the capillary. The window, *W*, was of fused quartz and was fixed to the ground end of the tube with Apiezon wax. The tube was mounted in a water bath and was held in place by the two clamps, *B*, so that the window *W* protruded from the tank. A rubber gasket held against the tank with a brass collar was waxed to the glass neck of the tube. A water jet was made from one-fourth inch copper tubing bent as shown and cut through its lower side up past the bend. The lower end was closed with a brass plug and the slot partially closed until a uniform sheet of water flowed from the slot.

Comparison with the carbon arc

For practical spectroscopy the question arises whether or not the hydrogen discharge is preferable to the carbon arc, its chief competitor, which emits a powerful continuous spectrum from its positive crater. The intensity per unit area of the arc is nearly constant in air at atmospheric pressure, for an increase in current does not appreciably raise the temperature but merely increases the area of the crater. There is no doubt that for long wave-lengths the carbon arc is far superior to the hydrogen continuum and that for short wave-lengths the hydrogen continuum is far superior. For practical purposes the limiting wave-length must be determined.

The tube was connected with the vacuum system and pumped out. After several flushings with hydrogen, the pressure was adjusted to 2.5 mm. The arc was mounted opposite to the capillary. Halfway between the two an aluminum surfaced mirror was placed so that an image of either the arc or capillary could be brought onto the slit of a quartz spectrograph. A filter of Corex red-purple glass was placed over the quartz condensing lens to prevent scattered visible light from the arc from fogging the plate. Exposures were made with a current of 1 ampere (128 ma/mm²) flowing through the tube. The voltage drop across the tube was 837 volts. The current through the arc was 5.5 amperes and the voltage drop was 61 volts. Under these conditions the two sources gave the same intensity at 2925A. Below this wave-length the hydrogen continuum of the discharge tube described is more intense than the continuum of the arc. The carbon arc spectrum increases in intensity so rapidly with wave-length that the two sources are nearly equal only within the narrow range of a few hundred angstrom units. If the discharge is used intermittently, as it is done for the chemical investigation mentioned below, it may be overloaded and so become equal to the arc for a little longer wave-length, perhaps 3050A, practically not much further. The intensity of radiation emitted by the positive crater of the arc, on the other hand, does not increase appreciably with increased current.

The discharge tube was sealed off and used by Frost and Oldenberg[17] in the investigation of the absorption spectrum of hydroxyl radicals. It needed refilling only after many hundred hours of operation. During its operation, no impurities appeared as practically all other molecules are adsorbed at a much faster rate than hydrogen.

The author takes this opportunity to express his appreciation to Professor O. Oldenberg, who suggested the problem, for his very material aid in carrying through the work and in preparing this paper.

[16] The capillary was made by Mr. H. W. Leighton, laboratory glass-blower.

[17] A. A. Frost and O. Oldenberg, J. Chem. Phys. **4**, 642 (1936).

Proceedings of the Twenty-Second Annual Meeting of the Optical Society of America

THE LAKE PLACID CLUB, ESSEX COUNTY, N. Y., OCTOBER 14–16, 1937

THE twenty-second annual meeting of the Optical Society of America was held at the Lake Placid Club, Essex County, N. Y., October 14–16, 1937.

The pleasant surroundings of the Lake Placid Club with its opportunities for recreation and informal discussions made this meeting of the Optical Society of America especially enjoyable and profitable to those who attended.

The meeting was opened Thursday, October 14, at 9:30 A.M. with a brief address of welcome by Mr. Samuel H. Packer, vice president of the Club.

INFORMAL SOCIAL GATHERING

Kodachrome lantern slides and Kodachrome motion pictures of the recent National Geographic-U. S. Navy Eclipse Expedition to Canton Island, taken by I. C. Gardner, Charles Bittinger and F. K. Richtmyer, members of the expedition, were shown at the informal social gathering on Thursday evening. These included black and white and colored motion pictures of the eclipse and views of the encampment on the island and of the observing instruments. In addition to the Society and its guests the pictures attracted a large number of guests of the club who were not registered for the meeting of the Society. As an additional feature Loyd A. Jones showed a series of remarkable Kodachrome motion pictures which had been awarded a medal at the annual exhibit of the Royal Photographic Society in London. These showed the beautiful color patterns which are formed by growing organic crystals, when viewed in polarized light.

SYMPOSIUM OF INVITED PAPERS ON OPTICAL MATERIALS

The symposium on optical materials Friday morning was unusually interesting and aroused much discussion. The following papers were presented in the symposium:

Optics and the Glass Industry. E. D. TILLYER, *American Optical Company.*

The Availability of Optical Glasses. GEORGE W. MOREY, *Geophysical Laboratory.*

Glass Requirements of the Optical Manufacturer. W. B. RAYTON, *Bausch & Lomb Optical Co.*

Optical Glass at the National Bureau of Standards. A. N. FINN, *National Bureau of Standards.*

Crystal-Growing for Optical Purposes. DONALD C. STOCKBARGER, *Massachuseits Institute of Technology.*

ANNUAL DINNER AND AWARD OF FREDERIC IVES MEDAL

The feature of the annual dinner Friday evening was the award of the Frederic Ives Medal to Dr. Herbert E. Ives of the Bell Telephone Laboratories.

In accepting the medal Dr. Ives recalled incidents in the life of his father in whose honor the medal was endowed, and exhibited some of the early lantern slides which his father had made, using the original three color mixing projection lantern constructed to exhibit them in natural colors.

At the close of the dinner President Hardy introduced the newly elected officers of the Society.

BUSINESS SESSION

A brief business session of the Society was held Saturday morning at 9:00 A.M., President Hardy presiding.

The formal reports of the Secretary, Editor of Publications, and Treasurer, for the calendar year 1936* were laid before the Society. The reports were supplemented by informal reports of the changes since January 1, 1937. The reports were accepted.

The Secretary was instructed to write to the Lake Placid Club expressing the appreciation of the Society for its hospitality which had contributed to a highly successful and enjoyable meeting.

* Published in J. O. S. A. **27**, 214, 216, 218, (1937).

Registration

Members 57, Guests 35, Total 92.

Sessions for the Reading and Discussion of Contributed Papers

Sessions for the reading and discussion of contributed papers were held as follows:

Thursday, October 14, at 9:30 A.M.
Saturday, October 16, at 10:00 A.M.

The authors' abstracts of these papers are appended.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Thursday afternoon, October 14. The minutes of this meeting are appended.

L. B. Tuckerman, *Secretary*

Minutes of the Tenth Meeting of the Directors of the Optical Society of America, Incorporated

Lake Placid Club, Essex County, N. Y., October 14, 1937

BESIDES the transaction of routine business, the following items of general interest to members of the Society were taken up.

Announcements by Secretary

W. E. Forsythe appointed member of Division of Physical Sciences of the National Research Council for the term to expire June 30, 1940.

An agreement vesting all responsibility for Associate Editors of the *Review of Scientific Instruments* in the American Institute of Physics, authorized at the meeting of March 4, 1937, was signed May 12, 1937.

Results of letter ballots:

1. Award of Frederic Ives Medal for 1937 to Herbert E. Ives.
2. Appointment of L. B. Aldrich, A. N. Finn and Dorothy Nickerson as tellers to make count of ballots for 1937 election of officers and directors.

Membership

The Secretary's report showed that since January 1, 1937 the membership had increased from 617 to 634, and that since the last meeting of the Directors 21 new members had been elected as of January 1, 1937 and 5 new members as of January 1, 1938.

The Secretary reported two deaths among the membership since the March meeting.

Transfer from Associate to Regular Membership

The following were transferred from associate to regular membership:

Ernst H. Anthes (951 R)
E. M. Brockway (937 R)
V. E. Carbonara (895 R)
G. H. Carragan (1060 R)
O. O. Ceccarini (583 R)
C. B. Coulter (1085 R)
F. L. Dimmick (1095 R)
R. H. Draeger (1063 R)
R. W. Duncan (915 R)
Roger S. Estey (848 R)
Edward E. Free (1065 R)
Martin Grabau (940 R)
Cedric E. Hesthal (1101 R)
Elmer Hutchisson (1088 R)
J. F. Leventhal (1035 R)
C. A. R. Lundin (1077 R)
Wm. O. Lytle (1068 R)
William Mayer (1076 R)
J. F. Neumueller (1030 R)
Kenneth N. Ogle (1075 R)
Roy A. Palmer (1086 R)
Allan E. Parker (1099 R)
G. M. Rassweiler (1074 R)
Frank J. Studer (1089 R)
Karl S. Weaver (1069 R)
John M. Wells (1100 R)

Financial Status of the Society

The treasurer gave an informal report which showed that the Society had maintained its excellent financial condition.

Election of Editor of Publications

F. K. Richtmyer was elected Editor of Publications for a term of four years ending in October 1941.

Appointment of Associate Editors of the Journal

The following associate editors of the *Journal of the Optical Society of America* were appointed for a term of six years ending December 31, 1943.

Frank Benford	A. C. Hardy
O. J. Davisson	G. S. Monk
L. A. Jones	G. R. Harrison

Election of Officers

The count of the official tellers showed that the following officers and directors had been elected:

For a term of two years beginning October 16, 1937:

President	R. C. Gibbs
Vice President	K. S. Gibson

For a term of four years beginning October 16, 1937:

Secretary	L. B. Tuckerman
Treasurer	Henry F. Kurtz

and, Members at Large of the Board of Directors:

H. P. Gage Wm. F. Meggers
Brian O'Brien

L. B. Tuckerman, *Secretary*

Program of Sessions for Contributed Papers

(Titles and Abstracts of Papers)

1. Effect of Aging on Thermometer Glasses. Bradford Noyes, *Taylor Instrument Companies.* (15 minutes.)

For over one hundred years it has been known that the volume of a thermometer bulb was subject to afterworking, or a change in the properties of the material of the bulb which might affect the reading of the instrument. Person[1] attempted to anneal the bulbs to overcome this difficulty. Special glasses for thermometric purposes were devised by Schott in Jena from 1880 to 1890, among these being the so-called "normal" glasses and the "borosilicate" glasses in common use at the present time. Dickinson[2] studied the effect of high temperature on thermometers of these glasses for as long as 1900 hours. More recently Holburn and Otto[3] have investigated the physical properties of thermometric glasses between the so-called strain and annealing points.

The present investigation shows that the change in the volume of the bulb may be considerable even after tubes have been artificially aged at high temperatures, the amount of the change depending greatly upon the temperature and time of aging.

Thermometers made of "borosilicate" glass and artificially aged are still showing slight changes in the ice point after more than two years, being held constantly at a temperature of 445°C. 490°C rather than 500 or 550°C, is probably the upper limit at which thermometers of this material should be used continuously. Other thermometers made of "normal" bulb glass and lead capillaries have also been studied and the change of the volume of the bulb measured.

These changes in volume may be due entirely to release of strain, but if so the strains are minute, as even short artificial aging removes all strains visible in a polariscope.

[1] Comptes rendus **19**, 1314 (1844).
[2] Bul. of the National Bureau of Standards, Vol. 2, No. 2.
[3] Zeits. f. Inst. **46**, 415–424.

2. The Design of Monochromatic Filters for the Type H-3 Mercury Lamp. Elizabeth M. Staats, *Fish-Schurman Corporation.* (Introduced by Ferdinand Schurman). (15 minutes.)

The present popularity of the type H-3 mercury lamp justifies a further consideration of mercury monochromats. The design of mercury monochromats represents a choice of glasses and thicknesses to achieve the highest efficiency (ratio of transmission at the designed wave-length to total transmission) permitted by the energy distribution of the source and the spectral response of the receiver.

The filter glasses (usually two) in the monochromat are selected by considering the steepness of slope of their transmission curves near the designed wave-length and their degree of opacity in adjoining regions. The proportionate thicknesses can then be varied for the most favorable values of transmission at the desired wave-length and of efficiency.

The best thickness ratio between the components is found by computing the efficiencies of several combinations whose total thicknesses are adjusted to give constant transmission at the designed wave-length. It is presumed that the best thickness ratio is practically independent of

the thickness of the total filter over the range investigated. By varying the total thickness, keeping the ratio constant, a relation between the transmission at the designed wave-length and the efficiency will be shown.

Monochromats have been designed for use with the type H-3 mercury lamp utilizing caesium and sodium surface phototubes, the selenium surface barrier layer cell, the thermopile and the eye as detectors. Curves will be given showing the best values of efficiency and transmission at the desired wave-length for the various source-filter-receiver combinations.

3. Artificial Daylight from Carbon Dioxide Lamps. THOMAS J. KILLIAN, *Barkon Tube Lighting Corporation.* (20 minutes.)

It has been known for many years that carbon dioxide has a densely filled, well-balanced spectrum with a luminosity distribution very close to that of slightly overcast north sky light. Carbon dioxide lamps furnish a very satisfactory source of artificial daylight for color matching, inspecting and other visual tasks. There are many problems attending the construction of such lamps. Due to the great activity of the ionization products, there is a continual disappearance or "clean-up" of gas. Furthermore, the light output is very sensitive to slight changes in gas density. Some auxiliary mechanism is therefore necessary to keep the pressure, which is of the order of a tenth of a millimeter, constant at all times. Various mechanical and magnetic methods have been used in the past. These methods are elaborate and very sensitive to small changes in line voltage.

A simple electronic method has been devised which maintains the pressure very accurately. Color matching lamps using this method are now available in wattages ranging from 200 to 800 with a rated life of 6000 hours. Due to the continual replenishment of the gas, there is little or no change of chromaticity over this rated life. The electrical characteristics of the lamps are discussed as well as the energy distribution of the radiation. A comparison is made of the trichromatic coefficients for various materials as obtained under I. C. I. Illuminant *C*, the sun outside the earth's atmosphere and under carbon dioxide lamps.

4. A High Dispersion Constant Deviation Monochromator for the Range 10,000 to 2,000 Angstroms. GEORGE R. HARRISON, *Massachusetts Institute of Technology.* (15 minutes.)

For absorption spectrophotometry a monochromator which will transmit light from 10,000 to 2000A with a minimum of optical adjustment is extremely desirable. Prism instruments suffer from large variation in wave-length dispersion, from low dispersion at long wave-lengths, and from the necessity of changing prism materials to cover the range with proper dispersion. Large light losses result from the great number of optical surfaces required, and to reduce scattered light a double monochromator must be used.

Diffraction gratings have hitherto been considered too light-weak for use in monochromatic illuminators. The new aluminum-on-glass gratings ruled by Professor R. W. Wood have changed this situation. A 15,000 line per inch concave grating of six inch aperture and ten meter radius has been mounted to serve as a high intensity monochromator of high dispersion. Measurements show that the overall transmission varies between 30 percent and 50 percent for visible and ultraviolet light, values much greater than are found for most single or double prism monochromators. The instrument is singularly free from scattered light, so that no auxiliary dispersing system is required except in extreme cases.

The monochromator is 18 ft. long by eight feet wide and gives a dispersion of 3.3 A/mm, which may be compared with the average of 50 to 100 A/mm given by most monochromators. Its great size makes possible the use of wide slits without serious sacrifice of spectral purity, if high light-gathering power is desired. The numerical aperture is *f*:23, which is considerably less than is common for prism instruments, but a six foot grating of six inch aperture would give *f*:6. The present instrument is also arranged for use as a stigmatic spectrograph.

The spectrum from 10,000 to 2000A can be run through in 100 seconds with an electric motor. The automatic adjustments which are made when this is done are rotation of the grating and a small motion of the exit slit along the optic axis. Entrance and exit beams have fixed directions, and the aperture ratio stays nearly constant. Deflections of several thousand millimeters can be obtained when a galvanometer is connected with a photo-cell and an incandescent lamp or mercury arc is used as a light source.

5. A Study of Polarized Vertical Illumination. L. V. FOSTER, *Bausch & Lomb Optical Co.* (20 minutes.)

The application of a polarizer to a vertical illuminator results in elliptical polarization. The illuminated field of the microscope is only partially polarized. An explanation of the reasons for this will be given. Numerous attempts to remove these faults have been attempted. Means to reduce elliptical polarization to a minimum will be described. A vertical illuminator free from elliptical polarization will also be described.

The present paper will appear in full in the J. O. S. A.

6. The Optical Constants of Rubidium and Caesium. HERBERT E. IVES AND H. B. BRIGGS, *Bell Telephone Laboratories, Inc.* (15 minutes.)

The optical constants of rubidium and caesium have been determined by the methods and apparatus used previously in a similar study of sodium and potassium.* The curves depicting the refractive index and extinction coefficients are, in general, similar in character in all four alkali metals, with a progressive shift toward longer wave-lengths in going from sodium to caesium.

The application of these data to the explanation of thin film photoelectric emission will be discussed.

* J. O. S. A., June 1936 and May 1937.

7. Fading of Dyes and Tendering of Fabric by Light as Problems for the Physicist. I. H. GODLOVE, *E. I. du Pont de Nemours & Co., Inc.* (20 minutes.)

When dyebaths or dyed fibers are illuminated and light is absorbed, the absorbed energy may take several alternative courses. It may: (1) activate, alter or destroy the dyestuff; (2) cause the excited molecule to react with the fiber or simply pass the extra energy along to the fiber and weaken it; (3) it may be emitted as fluorescence; (4) it may be dissipated as heat; or (5) as a case similar to the first, be absorbed by an added preventative.

In connection with the light-fastness of dyes and the tendering of fibers, for example, when the oxidation-reduction reactions are sensitized by vat dyestuffs, a great mass of uncoordinated facts has been accumulated by textile "colorists." On the other hand, physicists, and biologists interested, for example, in photosynthesis in green plants, have developed to a high state the laws of absorption and utilization of energy (Grotthus-Draper law, Einstein law, the quantum relation, existence of "activated states" and critical minimum thresholds, conditions for fluorescence or dissipation of heat, etc.). But no sustained effort to correlate the great body of facts in the light of the general principles has ever been made.

A review of the known facts and relevant principles has been made in this laboratory; and one practical application of the principles has been worked out in detail. The intimate relation of "fading" (including darkening) to tendering of cellulose fibers, especially in the presence of certain orange and yellow vat dyestuffs has been pointed out; also possible ways of improving fastness and preventing tendering by judicious mixture of dyes. A simple accelerated test for tendering has been worked out which depends on making a small amount of an ordinarily fast "direct cotton" dye bear the brunt of the light attack when "topped" upon a "tendering dye" of the vat class. Tedious and erratic tensile strength measurements are replaced by a quick judgment of color change. The routine test affords excellent correlation with general experience; and a start on preventative measures has been made.

It is suggested that physicists may be able to work out many other applications; for example, a differentiation of fading due to light or to atmospheric impurities, based upon the difference in the temperature coefficients of photochemical and ordinary thermal chemical reactions.

The present paper will appear full in the J. O. S. A.

8. Observations of a Searchlight Beam to an Altitude of 28 Kilometers. E. O. HULBURT, *Naval Research Laboratory.* (15 minutes.)

The beam of a high intensity searchlight directed over an observing station 18.4 km distant at angles of 30° and 45° to the horizontal was visible to a vertical altitude of about 20 km and was photographed to 28 km on clear nights. The intensity of the beam measured from the photographs was of the same order of magnitude as that calculated from the Rayleigh theory of molecular scattering using standard tables of stratospheric densities. At 5 km the observed intensity was greater than the theoretical intensity by a factor of about 7, the factor decreasing to about unity above 10 km, as would be accounted for by a small number of haze particles at 5 km which decreased to an imperceptible amount above 10 km.

9. Production of Isodensity Contours of a Photographic Negative. BRIAN O'BRIEN AND HAROLD S. STEWART, JR., *Institute of Optics, University of Rochester.* (15 minutes.)

Measurement of intensities by means of a wedge spectrogram requires the determination of position on plate of a contour line along constant photographic density. If emulsion used for original negative possessed sufficiently high gamma this contour would appear as a sharp boundary between clear and very dense portions of image. For this a gamma of 20 or more is required but is not possessed by any sensitive photographic material now available. We have tested, alone and in combination, the several published reduction and intensification techniques known to increase gamma, but gain is not sufficient to produce a sharp contour line, and uncertainties greater than attributable to emulsion irregularity are introduced into photometric result. An alternate method consists of multiple printing upon high gamma positive material. Eastman Kodalith emulsion (not orthochromatic) may be developed under proper conditions to a gamma of 6 or 7. A master positive and duplicate negative on this material will thus yield an overall gamma of 40 or more, the image boundaries of the duplicate negative providing a very sharp isodensity contour of the original negative. The usual processing technique for Kodalith emulsion introduces small irregularities which are greatly magnified by the high over-all gamma of the duplicate negative. Factors producing these irregularities have been investigated and largely eliminated, so that a high degree of reproducibility is now secured.

This procedure is also applicable to a variety of photometric problems such as brightness distribution in field of a projection system, brightness distribution over surface of sun, isophot contouring of nebulosity in astronomical photographs etc. Repetition of procedure at successive exposure levels produces contour lines at successive density levels of original negative, permitting construction of a complete isophot contour map.

10. Optical Study of Solar Coronal Photographs of June 8, 1937. BRIAN O'BRIEN, H. S. STEWART, JR., AND C. J. ARONSON, *Institute of Optics, University of Rochester.* (15 minutes.)

Eclipse photographs of June 8, 1937 secured by Major A. W. Stevens from airplane at elevation of 25,000 feet on Hayden Planetarium—Grace Expedition to Peru were observed by Stevens[1] to exhibit unusual amount of diffuse luminosity surrounding sun and of different appearance from usual solar corona. Such luminosity could result from one type of diffraction pattern due to particles (such as ice crystals) suspended in atmosphere above camera level. To distinguish between this and a true solar phenomenon we have produced, using the technique described in preceding abstract, a series of isodensity contours of each of a series

of negatives made with two cameras throughout duration of totality. It can be shown that if the luminosity is due to atmospheric diffraction the center of the isodensity contours will shift from beginning to end of totality by an amount of the order of sun's radius. No shift was observed, although an amount 1/30 sun's radius in the photographic image could be detected. This was further emphasized by laboratory photographs of artificial light source simulating inner coronal ring at second or third contact, diffracting particles of proper size and distribution being introduced between source and camera objective. Our conclusion is that luminosity observed by Stevens is of solar not atmospheric origin, and is a part of the solar corona.

Isodensity contours of coronal image depart only moderately from concentric circles and show little of coronal streamers so pronounced in ordinary direct photographs. Contours of similar form have been secured by Bergstrand[2] and von Klüber[3] using point to point measurements with modified Hartmann photometers. Nevertheless the almost spherical symmetry of coronal luminosity does not appear to have been appreciated, probably because of a visual illusion. The ability of the eye to detect very small discontinuities in brightness while ignoring large but gradual brightness transitions across visual field accounts for prominent appearance of coronal streamers which, as shown by this work, are actually only slight, though abrupt, transitions in brightness, and are a secondary phenomenon superimposed upon the diffuse luminosity surrounding the sun which is the outstanding feature of the corona.

Significance with relation to coronal theories is discussed briefly.

[1] To be published shortly.
[2] Bergstrand, Off. p l'Obs. Astro d'Upsala (1919).
[3] von Klüber, Zeit. f. Astrophys. **3**, 142 (1931).

11. Precision and Accuracy of Apparent Reflectance Measurements with a Photoelectric Illumination Meter. RICHARD S. HUNTER, *National Bureau of Standards.* (10 minutes.)

There are several photoelectric illumination meters[1] on the market, each consisting of a barrier-layer photo-cell and a sensitive ammeter which is graduated so that the illumination upon the exposed face of the photocell registers directly in foot candles. These meters are small, portable and relatively inexpensive. Used with a controlled and properly placed source of light and means for locating the surfaces of samples to be measured, a photoelectric illumination meter may be made to make apparent reflectance measurements upon such surfaces with a precision equal to that of the meter.

A portable instrument to measure both 45°–45° specular gloss and 45° normal apparent reflectance using a photoelectric illumination meter has been built and will be described. This instrument, somewhat similar in principle to those used by others, should prove useful to persons who wish to make rapid measurements on paint panels, papers and other materials and who do not need the highest precision as, for instance, in tests of products for compliance with reflectance and gloss specifications. For specular gloss measurements special attention has been given to the size of the apertures. For 45° normal reflectance measurements a filter is used correcting the spectral sensitivity of the barrier-layer photo-cell and source combination to approximately that of the luminosity function.

It was not difficult to reproduce readings with deviations of less than 2 percent of full scale. Test measurements on standard porcelain-enamel plates, both selective and nearly neutral, indicated that measurements of 45° normal reflectance could be obtained for all but the most saturated colors with accuracy of the same order of magnitude.

The values obtained on this instrument will serve to indicate the precision and accuracy obtainable with photoelectric illumination meters in general as well as the possible usefulness of the present device.

[1] See "Report of the Committee on Photoelectric Portable Photometers," Trans. I. E. S. **32**, 379 (1937) for a description of various barrier-layer photo-cells and illumination meters made therefrom.

12. Development of Filters for Tri-Stimulus and Luminosity Measurements with Barrier-Layer Photo-Cells. RICHARD S. HUNTER, *National Bureau of Standards.* (10 *minutes.*)

Among the problems to which barrier-layer photo-cells are frequently applied are those having to do with colorimetric measurements. It has been pointed out by Gibson[1] that, whereas a number of users of these cells have attempted to make tri-stimulus colorimetric measurements for general purposes with barrier-layer cells and spectral filters, few if any investigators have used filters that enable values to be obtained which can properly be called tristimulus specifications, particularly as applying to any standard colorimetric system. Directions were given, however, for computing, from the spectral sensitivity of a photo-cell and the spectral energy distribution of a source used in an instrument, the spectral transmissions of filters which must be employed to obtain tri-stimulus and luminosity measurements for a given colorimetric coordinate system and illuminant.

It is the purpose of the present paper to describe progress in obtaining glass filters having the proper spectral transmissions for one type of photo-cell used under one set of conditions. Manufacturers' data on the G. E. Hewlett cell and the Weston type 2 cell, which indicate that the two cells are very similar in spectral sensitivity, were used to define the receptor element of the system. These cells were chosen because of their high sensitivity in the blue end of the spectrum. The filters sought were such that when used with an actual source at 3100°K they would give data on the I. C. I. standard colorimetric system and for I. C. I. Illuminant *C*.

The best set of glasses so far tested are the following three pairs:

(a) For the "*X*" function (with that portion of the function between 380 and 500 μ made zero): Corning 330 signal yellow, 6.7 mm of melt of 11–9–31, with Corning 397 medium shade aklo, 2.0 mm thick.

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(b) For the "*Y*" (luminosity) function: Corning 330 signal yellow, 2.7 mm of melt of 11–9–31, with Corning 428 light shade blue green, 3.5 mm of melt of 7–20–35.

(c) For the "*Z*" function: Corning 554 lantern blue, 4.4 mm of melt of 2–13–35, with Jena GG3, 1.5 mm of melt No. 25287.

Comparisons of the ideal and actual transmissions will be shown and some data given on the performance of the cells with these filters in deriving I. C. I. colorimetric values.

[1] K. S. Gibson, "Photoelectric 'Colorimeters,'" National Bureau of Standards LC473, July 1936, and Instruments **9**, 309 (1936). For the description of a "*Y*" function filter for another cell and the method by which transmissions of filters of different thicknesses may be computed see Gage, J. O. S. A. **27**, 159 (1937).

13. Correction Terms Correlating Color Temperatures Based on the Wien and the Planck Radiation Formulas. ROGER S. ESTEY, *Spencer Lens Company.* (10 minutes.)

The very convenient relationships between the color temperatures of sources and the color temperature altering power of filters in which color temperatures are expressed in reciprocal form were derived from Wien's formula for the spectral distribution of energy as a function of temperature. At temperatures lower than 5,000°K the Wien and Planck formulas yield substantially the same spectral distributions of energy, but at higher temperatures these energy distributions become progressively dissimilar. This makes a table of corrections by which the color temperatures on the Wien basis may be readily converted to the more common Planck basis and *vice versa* of value to those interested in high color temperatures.

To obtain such a correlation a series of spectral distributions have been computed according to the Wien equation for temperatures ranging from 4000 to 18,000°K. The trilinear color coordinates have been computed using the I. C. I. constants and the Planckian temperature colors closest to the Wien temperature colors estimated with the aid of a series of iso-temperature lines.

From this correlation of color temperatures a table of corrections was obtained for finding the color temperature of a Planckian spectral distribution of energy having the same color as a similar distribution based on a selected temperature value used in the Wien formula. These corrections are tabulated below:

Terms to add to color temperatures expressed on the Wien basis to convert them to the Planck basis.

Color Temperature, Wien	Additive Correction	Color Temperature, Wien	Additive Correction
5000°K	28°K	12,000°K	1950°K
6000	75	13,000	2770
7000	158	14,000	3845
8000	293	15,000	5240
9000	512	16,000	6880
10,000	840	17,000	8770
11,000	1310	18,000	10,740

It is estimated that these corrections are correct within about ± 5 percent. This correlation will be of value to those wishing to make color temperature calculations at temperatures above 5000°K.

The present paper will be submitted to the J. O. S. A.

14. Uniform Tolerances for Surface-Color Specification. DEANE B. JUDD, *National Bureau of Standards.* (20 minutes.)

An opaque surface-color may be specified by apparent reflectance, A, trilinear coordinates, r, g, b,[1] and specular gloss, G_s.[2] Color deviations from a standard surface may be expressed by the differences, ΔA, Δr, Δg, Δb, and ΔG_s. If sample and standard have the same gloss ($\Delta G_s = 0$), the following formula gives a function of these differences which has been found to be approximately proportional to the perceptibility of the color difference under specified observing conditions:

$$\Delta E = [6AB_0/(AB_0+0.05BG_s)] \times (A^{\frac{1}{2}}\overline{\Delta S}^2\times 10^4+0.005\overline{\Delta A}^2\times 10^4/A)^{\frac{1}{2}},$$

where $\overline{\Delta S}^2$ is an abbreviation for $\overline{\Delta r}^2+\overline{\Delta g}^2+\overline{\Delta b}^2$. The observing conditions are: (1) sample and standard lying horizontally on a table in front of a window and illuminated chiefly by light from the sky, (2) sample and standard viewed nearly along the perpendicular and interchanged as a test for uniformity of illumination, and (3) sample and standard covered with an equivalent gray mask having two holes of the same size and shape permitting the sample and standard to be seen with a gray band separating them.

If the sample and standard are glossy the detection of the difference between them is interfered with by mirror images of ceiling and walls of the room even though images of brighter areas such as the sky be avoided; the effect of this interference is to reduce the color difference. The essence of this situation is expressed by the relation between the brightness, B, of the actual surface which is in position to be mirrored in the glossy surface of the sample and the equivalent hemisphere brightness, B_0, which is the brightness that a uniformly bright hemisphere would need have to provide the sample with its actual illumination.

The constant 0.005 has been found to vary with the width of the area dividing the sample from the standard; this constant should be more than 0.01 if there is no dividing area at all, and it should be considerably smaller than 0.005 if the dividing area is conspicuous. The constant 6 defining the units in which this formula expresses color difference has been adjusted so that $\Delta E = 1$ corresponds to a difference of some commercial importance. This difference is small enough to be neglected in some industries, but it is large enough to cause argument in others; it is equivalent to $\frac{1}{4}$ of the chromaticity difference between the components of the sodium D line. A number of pairs of samples will be exhibited which exemplify this difference, and data will be presented showing for a few cases the extent to which subjective estimate of color differences disagrees with estimate by means of this formula.

[1] J. O. S. A. **25**, 24 (1935).
[2] Nat. Bur. Stand. J. Research **18**, 19 (1937); RP958.

15. A New System of Photometric Units. E. C. CRITTENDEN, *National Bureau of Standards.* (15 minutes.)

The International Committee on Weights and Measures at its meeting in June, 1937, adopted a new system of photometric units intended to replace both the "International" and the Hefner units. This action is expressed in a resolution translated as follows:

1. Beginning January 1, 1940, the unit of luminous intensity shall be such that the brightness of the blackbody radiator at the temperature of solidification of platinum will be 60 candles per square centimeter.

This unit will be called the "new candle" ("bougie nouvelle"), with appropriate translation into the various languages.

2. (a) The values for photometric magnitudes of sources of light differing in color from the primary standard shall be determined by a procedure consistent with the luminosity factors, formerly called "visibility factors," adopted by the International Committee on Weights and Measures.

(b) To assure uniformity among the national laboratories of the different countries in passing from the new primary standard to secondary standards of the incandescent-filament type operating at higher efficiency, the procedure adopted for the present is the use of blue filters which, interposed between the photometer and one of the standards to be compared, will make the colors in the two parts of the photometric field the same.

While the action of the International Committee establishes the principle of the new system, the determination of precise values for working standards will require considerable time. Determinations in different laboratories will be necessary, and standard lamps of various types must be exchanged between countries for comparisons. Standards on the new basis must then be provided for lamp factories and testing laboratories in each country. It is not likely that all the measurements and all the formalities of final agreement can be completed in less than two years. The effective date of January 1, 1940, was set with this fact in mind. It also has the advantage of making the photometric changes coincide with a small adjustment of electrical units which is scheduled for the same date.

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